SA/PR 113

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A preliminary analysis of some Flambeau data

by

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Summary

Three burns are covered: 760-1, 760-2, and 460-14. Temperatures, thermal radiation, etc. were analysed, but not air movements or pressure measurements. A standard empirical intensity-time curve was fitted to all of them, allowing intensity and time scale factors to be determined. The standard curve can be used in calculating the protection afforded by shelter and to calibrate the wood block system of instrumentation. It is hoped that the time scale factors constitute a measure of the burning rate and might ultimately serve to check various theories. However, discrepancies have been found between different elements and there were not sufficient data to resolve them.

Introduction

1. Flambeau is a project to study mass fires by burning arrays of piles of forestry fuel. All piles are ignited simultaneously by jellied petrol cartridges.

2. This is the report of a hasty analysis of data received in the U.K. from the Riverside Laboratory, U.S. Forest Service, (1, 2 and 3) together with Countryman's article in Fire Technology (4). Three burns are covered: 760-1, 760-2, and 460-14. Their vital statistics are shown in Table 1.

3. The main point of the analysis was to get measures of the burning rate by fitting standard curves to the time variation of various elements:- Street temperatures, flame temperatures, thermal radiation, toxic gas concentrations, total and radiant fluxes, and weight loss rates. With further theoretical work it might prove possible to analyse soil temperatures in a similar way, but this has not yet been done. No use has been made of meteorological data, air movements or pressure measurements. The space variation of burning rate should provide a check on various theories of interaction (5) and the standard curves should help in assessing the protection afforded by shelters.

Method of Analysis

4. In most cases the raw data were extremely irregular and variable. A preliminary smoothing was carried out; in the case of graphical data by pencilling in an average curve by eye, and in the case of numerical data by taking means over a period of a few minutes.

5. The analysis was based on the assumption of theories 20a and 20b (5), that all these intensity-time histories can be represented by one or more standard curves. To do this, it is necessary to fit:-

(a) The time scale factor

(b) The intensity scale factor

and (c) The time scale origin

(There is no difficulty about the intensity scale origin, because this is either zero, as with Weight Loss Rate, or the ambient pre-burn value, as with temperature). The curves all seem to be skew, with a long tail at late times, so a Pearson Type III distribution was tried. This did not fit satisfactorily, and it was decided to fit a wholly empirical curve.

6. The two scale factors can obviously be easily fitted by plotting on log-log paper, but this leaves the problem of the time scale origin. The obvious solution is to take this as the ignition time, but this makes the curve depend on the early stage of fire growth after ignition, which is not of much interest in Flambeau, and can be pretty variable. The next possibility is to take it as the time of peak intensity, but this has 4 disadvantages:-

(a) The curve is split into two separate segments, with the peak itself off the paper.

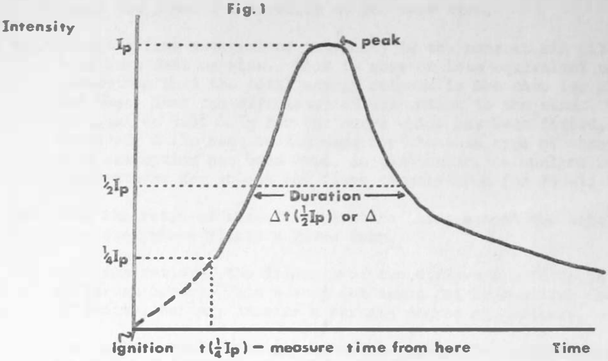
(b) Many of the curves finish before the peak is reached

(c) Some have very flat peaks

and (d) Some have double peaks.

The solution adopted was to measure time from the moment when the intensity first reached $\frac{1}{4}$ of the peak intensity (see Figure 1). This is not an ideal

Fig. 1



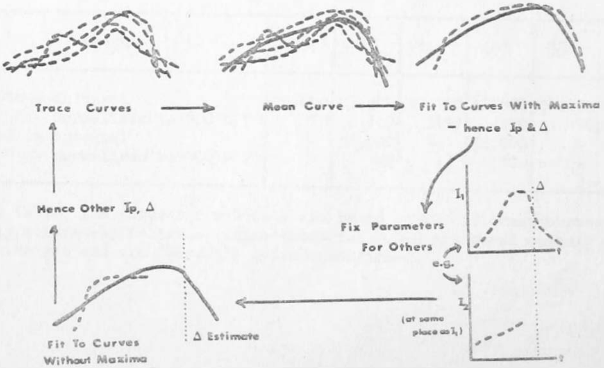
solution, but it is believed that it should reduce such errors to acceptably low levels. For example, so long as the curve goes on for a substantial time, even if it does not reach the peak, it should be possible to guess the peak intensity with sufficient accuracy that there cannot be any great error in the time of $\frac{1}{4}$ peak intensity.

7. As stated above, Ip was plotted against t - t($\frac{1}{4}$Ip) on log:log paper. The scale factors were characterised by Ip, the peak intensity, and Δ t ($\frac{1}{2}$ I p), the duration at more than $\frac{1}{2}$ the peak intensity - written as Δ.

8. Out of a total of 49 curves two have been rejected. The first was the flame temperature for Pile B3, Burn 760-1, rejected because the readings continued for such a short time. The second was the flame temperature for Pile C10 (or Position 29), Burn 460-14. This was based on one sensor only, the results were quite inconsistent with flux measurements on the same pile, and most of the time when the pile was burning fiercely the sensor was merely measuring the temperature of cold air (2).

9. There is no great difficulty about fitting if the curve has a clear and satisfactory peak. In the case of curves that have not, a further assumption is needed to be able to fit; but afterwards these also can contribute to the shape of the curve. Because of this feedback, fitting has been done by a process of successive approximation, as shown in Figure 2.

Fig. 2



BY SUCCESSIVE APPROXIMATION

10. There are a number of different further assumptions that can be used:-

(a) That Δ is the same for all curves at the same point, or relating to the same pile. This is justified by the observation that in such cases the peaks are normally at the same time.

(b) That the time integral of intensity is the same at all piles, whether they burn fast or slow. This is more or less equivalent to the assumption that the total energy release is the same for all piles, and hence that the efficiency of combustion is the same. The integral is equal to 1.68 Δ.Ip for the curve which has been fitted, so the value of Δ .Ip must be the same for the same type of observation. This assumption has been used, in particular, to analyse street temperatures for 460-14 and flame temperatures for 760-1.

(c) That the ratio of street temperature integrals at two heights is the same everywhere within a given burn.

(d) That the ratio of the integrals of two different effects is the same on different burns. This assumption seems fairly doubtful (see Paragraph 17 below), but may provide a certain degree of guidance.

(e) The ratio between street temperature integrals in different arrays can be calculated by the inverse square law - theories 3a and 3c (5). This give the ratios $\frac{760-2}{760-1} = 7.19$ and $\frac{460-14}{760-1} = 10.01$.

When several of these methods were available a weighted mean was taken, the weight depending on the number of observations and the directness of the inference.

Results

11. Figure 3 shows the curve which has been fitted. The dots indicate the degree of spread around it, which is also shown by the lines of ± 1 and 2 Standard Deviations. The curve has also been tabulated in Table 2. Δ is equal to 2.80 x peak time (measuring from time of $\frac{1}{4}$ peak), and, as stated, the integral from 0 to infinity is 1.68 Δ . Ip. However, there is a shortage of points towards the end of the curve, and depending on the slope chosen, the integral could be almost indefinitely larger (it could not be very much smaller). A single curve has been used to fit all the observations, i.e. theory 20a (5) has been followed - but see the end of Paragraph 17.

12. Table 3 shows the average height variation of the integrals of street temperatures.

Table 3

Height Variation of Street Temperatures

Height	3.5'	7'	13.5'	20'	35'	50'
460-14 - integral	19,000	25,300	30,100	32,800	34,400	35,400
" " - normalised to 100 @ 7'	75	100	119	130	136	140
760-2 - integral	-	32,000	-	32,000	-	21.500
" " - normalised to 100 @ 7'	-	100	-	100	-	67

In this table, the figures for 460-14 are based on 20 different curves and are probably moderately reliable, while those for 760-2 are based on only one curve at each height and are therefore quite unconfirmed.

13. Table 4 shows, for each of the 47 remaining curves, the values of Δ , Ip and the time integral, calculated by the methods of Paragraph 10. In addition, these values are shown calculated by direct fitting, as in Paragraph 9, where this was possible. These, fitted only from the curve itself, are more relevant when checking consistency and the assumptions of Paragraph 10. The times of the more important peaks (measured from ignition time) and the gap between ignition and t ($\frac{1}{4}$ Ip) are also quoted.

14. The duration Δ should be inversely proportional to the burning rate, so it seems reasonable to use this as a measure of it. Table 5 shows the mean duration at each location, where this is known.

Discussion

15. Figure 4 shows the durations for 760-1. As would be expected with this wide separation, there seems no evidence of any important variation or interaction. The dry-bulb temperature results are of considerable interest. The upwind station, P3, has somewhat lower integrals than P1 and P4, which are at the same distance from the array but downwind or crosswind. Moreover, the interior station P2 has an integral 2.68 times the mean of P1, 3 and 4 (using the directly fitted figures), which compares with a ratio of 2.96 calculated on the assumptions of Theory 3 (5). This agreement tends to confirm these assumptions, viz:-

(a) The temperature rise at a point is the sum of the contributions from each of the piles.

(b) The contribution is proportional to the burning rate (assumed equal for all 9 piles).

(c) The contribution is inversely proportional to the square of the distance (confirmed for 80' - 450').

16. Figure 5 shows the Mean Durations for 460-14. A set of contours have been added based entirely on the street temperatures; if the other measurements are for the moment ignored it can be seen that:-

(a) There are important variations from place to place.

(b) On these 6 points, the spacial variation seems very smooth and regular, rather than random variation between piles; but the other measurements tend to contradict this. On the other hand, qualitative accounts by observers support it.

(c) The variation is not radial and does not seem to be due to wind effects - the ambient wind was almost a dead calm.

Hence interaction at peak whether due to wind (Theory 4 (5)) to gas composition and temperature (Theory 5) or to thermal radiation (Theory 6) does not seem to explain the results, and yet there did seem to be interaction, from (b). The explanation might possibly be that interaction was by ignition or re-ignition, before peak (Theory 2c).

17. The 3 remaining Durations for 460-14 are all relatively low, but do not agree with the street temperatures or with each other. Possible explanations include:-

(a) Despite the evidence in Paragraph 16, there are large random variations from pile to pile.

(b) The weight loss measurements, which were only made on $\frac{1}{4}$ of one pile and do not give a very good shaped curve, are to be discounted. However, the integral 6700 lbs. was very close to the total weight on the platform, 7000 lbs.

(c) Similarly the flux measurements might be discounted.

(d) The Thermal Radiation Duration was low because the edge of the array burnt faster. This would suggest some version of Theory 4, or Theory 5 if the effect of fire gases is to depress the burning rate.

(e) The Thermal Radiation Duration was low because smoke accumulated during the burn, greatly reducing the intensity at a later stage and moving the peak to an earlier time.

(f) The Thermal Radiation Duration was low because early on there was a big flame and intense sideways radiation; but later, although the burning was still continuing at a great rate most of the heat was emitted by upward radiation and by convection - the radiometer could see little but the cold outsides of logs.

(g) The street temperature durations were high because hot gas was steadily accumulating in the streets during the burn.

(h) The street temperature durations were high because until the low level air had been used up hot air did not come down into the streets (Theory 5a). Against this, there does not seem to be any evidence that the temperature rose faster at 50' than at 3.5'.

It does not seem possible to distinguish between these explanations on the evidence now available. It should be noted that the last 4 involve systematic differences between the elements - i.e. Theory 20b rather than 20a.

18. There are not many durations available for burn 760-2. It seems that this may have burnt somwhat faster than 760-1, and much faster than 460-14. As before, the duration for radiation is a lot shorter than for street temperatures, which tends to confirm that there is a real effect; but it might be either a radiation/temperature effect, or an outside/inside effect (the radiometer was on the outside of the array, whereas street temperatures were taken inside, in both cases). In this burn the variation of toxic gases (over a pile) was not inconsistent with that of flame temperatures, whereas in 460-14 the toxic gases (in the street) did not seem to correlate well with street temperatures. As shown in Table 3, the street temperatures seemed to fall with height instead of rising as in 460-14. If this observation is valid, it suggests that vertical circulation was much more important in this case - leading perhaps to some version of Theory 5.

19. Table 4 also shows data for 5 curves from Countryman's paper (4). These have not been used in the analysis, since it is not known where they were, or in which burn, but they were all good shaped curves. It is therefore interesting that the standard curve, which was derived without reference to them, fits them all extremely well.

Recommendations for Future Work

20. Not enough observations were available here to answer many of the vital questions. In future, it is suggested:-

(a) We need an extensive set of measurements all on the same element throughout the array. This could be provided by the wood block system, which could be calibrated using the standard curve.

(b) We also need timed readings at a limited number of points. It is very important that these should go on for a long time after the peak.

(c) The discrepancy between temperature, thermal radiation etc. needs clearing up. This could be done by intensive observations on single isolated piles. Thermal radiation usually gives very good curves - if only we can rely on it. Weight loss is very fundamental - if it can be got to provide good curves.

(d) To check interaction effects, one or more isolated piles should always be burnt at the same time as any array.

(e) We need to know whether a small proportion of fire gases in the input air increases or decreases the burning rate. This could be discovered in the laboratory.

References

1. U.S. Forest Service, Forest Fire Laboratory, Riverside, Cal. "Test Fire 760-1, Book 1" (Brown Folder).

2. As above "Test Fire 460-14" (Brown folder).

3. As above untitled blue folder with data on 760-2 and 460-14.

4. C. M. Countryman "Mass Fire Characteristics in Large-Scale Tests". Fire Technology Vol.1 No. 4. pp. 303-317.

5. A. M. Western "Some simplified theories about mass fires". SA/PR 102 (revised) Home Office, Scientific Adviser's Branch.

January, 1967.

Table 1 : Particulars of the three burns

Data	burn :-		
	760 - 1	460 - 14	760 - 2
Pile dimensions	47'x 47'x 7'	47'x 47'x 7'	47'x 47'x 7'
Pile weight	20 tons	20 tons	20 tons
Pile energy (BTU)	340×10^6	340×10^6	340×10^6
Width of streets (pile separation)	115'	25'	25'
Number of piles	3 x 3 = 9	18 x 18 = 324	6 x 6 = 36
Size of array	371'x 371'	1271'x 1271'	407'x 407'
Ignition : Date/time	Jan.31,1964/1005	Dec.6,1965/1215	May 15,1964/0830
Lapse rate		Stable-inversion -unstable	Unstable
Air temperature	39°F	43°F	59°F
Relative humidity	27%	61%	45%
Wind speed	3 - 5 knots	0 - 3 knots	3 - 5 knots
Wind direction	Easterly	Variable	Easterly
Ground	Dry	Under 4"-6"snow	Dry
Moisture content - fine fuel	11%	14%	12%
Moisture content - heavy fuel	20%	25%	20%
Burning rate		Very low	High
Burning efficiency		Very high	Low

Table 2 : The standard intensity-time curve

t (mins)	I (arbitrary units)
0	0.25
0.01	0.34
0.02	0.43
0.03	0.49
0.04	0.53
0.06	0.60
0.08	0.66
0.10	0.71
0.15	0.79
0.20	0.86
0.25	0.91
0.30	0.96
0.35	1.00
0.40	0.99
0.45	0.95
0.50	0.90
0.55	0.85
0.60	0.80
0.7	0.71
0.8	0.65
0.9	0.59
1.0	0.52
1.2	0.44
1.4	0.38
1.6	0.33
1.8	0.29
2.0	0.26
2.5	0.21
3.0	0.166
3.5	0.130
4.0	0.103
4.5	0.080
5.0	0.067
6.0	0.045
8.0	(0.017)
10.0	(0.004)

Notes

1. These values have been calculated for Δ = Ip = 1. For other values of Δ and Ip, scale proportionately.
2. All times are measured from t($\frac{1}{4}$Ip), the time of $\frac{1}{4}$ Peak Intensity.
3. Values from t = 6 onwards are extrapolated and highly uncertain.

Table 4: Parameters of all the curves

Burns	Element	Height (ft)	Location	Peak Times (1)	t(½ Ip) - t ign	Best Values Δ	Best Values Ip (2)	Best Values Integ.	Directly fitted values Δ	Directly fitted values Ip	Directly fitted values Integ.
760-1	Flame Temperature	7	Pile A1	8	1	17.5	1100	31,000	17.5	1250	36,000
"	"	7	" A2	8	1				17.5	910	26,000
"	"	7	" A3	5, 17	1				16	1150	30,000
"	"	7	" B1	4½	1½				18	1000	30,000
"	"	7	" B2	4	0				17.5	1050	30,000
"	Street Temp. (Dry-Bulb)	4½	Station P2	9-	3	20	20	670	24	17.5	690
"	Outside " " "	4½	" P1	16-, 78+	4		7	236		6.8	267
"	" " " "	4½	" P3	16-, 78+	4					5.1	222
"	" " " "	4½	" P4	16-	4					7.3	281
460-14	Total Flux	10	Pile C10 (29)	9 & 34	4	89	5.6	830	90	5.3	790
"	Radiant Flux	10	" " "	9 & 31	4		3.5	500	75	3.4	420
"	Weight Loss	-	" D10	5½, 22	3	24	170	6700	27	155	6800
"	CO2 Concentration	50		13, 37, 102	2	32	0.81	43	34	0.85	47
"	Thermal Radiation		Station 60 (50's of array	7, 18, 30	3½	51	1900	160,000	58	1700	160,000
"	Street Temp.	3½	Station T6	10, 16, 28, 37, 49	4½	116	100	18,950			
"	"	7	" "	10, 28, 50	4	117	135	25,265			
"	"	13½	" "	10, 15, 30, 58	4½	92	195	30,066			
"	"	20	" "	10, 38, 50	1	124	161	32,845			
"	"	35	" "	10, 30, 55	2½	118	180	3.,360			
"	"	50	" "	13, 50	1½	170	130	35,371	110	140	25,000
"	"	3½	" T7	11, 17, 35	2½	80	143	18,950			
"	"	7	" "	12, 35	3½	89	178	25,265			
"	"	13½	" "	12, 17, 25, 35	3	90	200	30,066			
"	"	20	" "	12, 35	3	69	290	32,845			
"	"	35	" "	11, 17, 25, 32	2	84	255	34,360			
"	"	50	" "	11, 23, 33	2½	56	390	35,371	72	390	45,000
"	"	7	" T30	37+	15	170	92	25,265			
"	"	20	" "	37+	5	190	105	32,845			
"	"	7	" T36	17, 42, 70+	7	90	175	25,265			
"	"	20	" "	17, 42, 73+	5	105	190	32,845			
"	"	7	" T37	12, 27+	5	145	106	25,265			
"	"	20	" "	27+	7	110	180	32,845			
"	"	7	" T38	6, 20, 34, 60	5	96	160	25,265			
"	"	20	" "	6, 37, 71+	5	100	200	32,845			
760-2	CO Concentration		over fuel pile	8-	3	15	1.15	29	17.5	1.1	31.5
"	CO2 "		" " "	8	3	15	4.9	115	15.5	5	126
"	Thermal Radiation		Station W1 (50's of array)	3.1, 5, 8	2	3.3	3600	46,000	3.4	8100	45,500
"	Flame Temp.	7		3.5, 5, 15+	3	15	2550	63,000			
"	"	20		5+	3	15	2550	63,000			
"	Street Temp.	7		3, 7	2	14	1400	32,000	14	1400	32,000
"	"	20		3, 9	2	14	1400	32,000	14	1500	34,000
"	"	50		4, 7	2½	14	950	21,500	9.7	980	15,000
?	Thermal Radiation		100' from fire edge	16	10				14.5	710	17,300
"	Dowel Temp.	2	6' from fire	22	10	29	205	10,000	36	200	11,700
"	"	2	53' " "	21	10		95	4,600	29	95	4,600
"	"	2	20' " "	18	10		26	1,270	18	27	780
"	Flame Temp.	22		21, 30, 42	13½				31	1900	99,000

Notes (1) All times in minutes. These are measured from ignition. A principal peak is underlined. 78+ means the curve ended at 78 minutes and peak had not been reached. Similarly with 16-.

(2) All temperatures in °F, Fluxes in BTU/ft^2/sec, concentrations in %, Thermal radiation in BTU/ft^2/hr.

Table 5 : Mean durations at various locations

Burn	Location	Element	Duration Δ (minutes)
760 - 1	Pile A1	Flame temperature	17.5
"	" A2	" "	17.5
"	" A3	" "	16
"	" B1	" "	18
"	" B2	" "	17.5
"	Stations P1,2,3,4	Dry-bulb temperature	20
460 - 14	Pile C10	Total & radiant flux	89
"	" D10	Weight loss rate	24
"	R - 50' from array	Thermal radiation	51
"	Station T6	Street temperature	120
"	" T7	" "	73
"	" T30	" "	182
"	" T36	" "	83
"	" T37	" "	129
"	" T38	" "	94
760 - 2	W1 - 50' from array	Thermal radiation	3.3
"	Centre	Street temperature	14

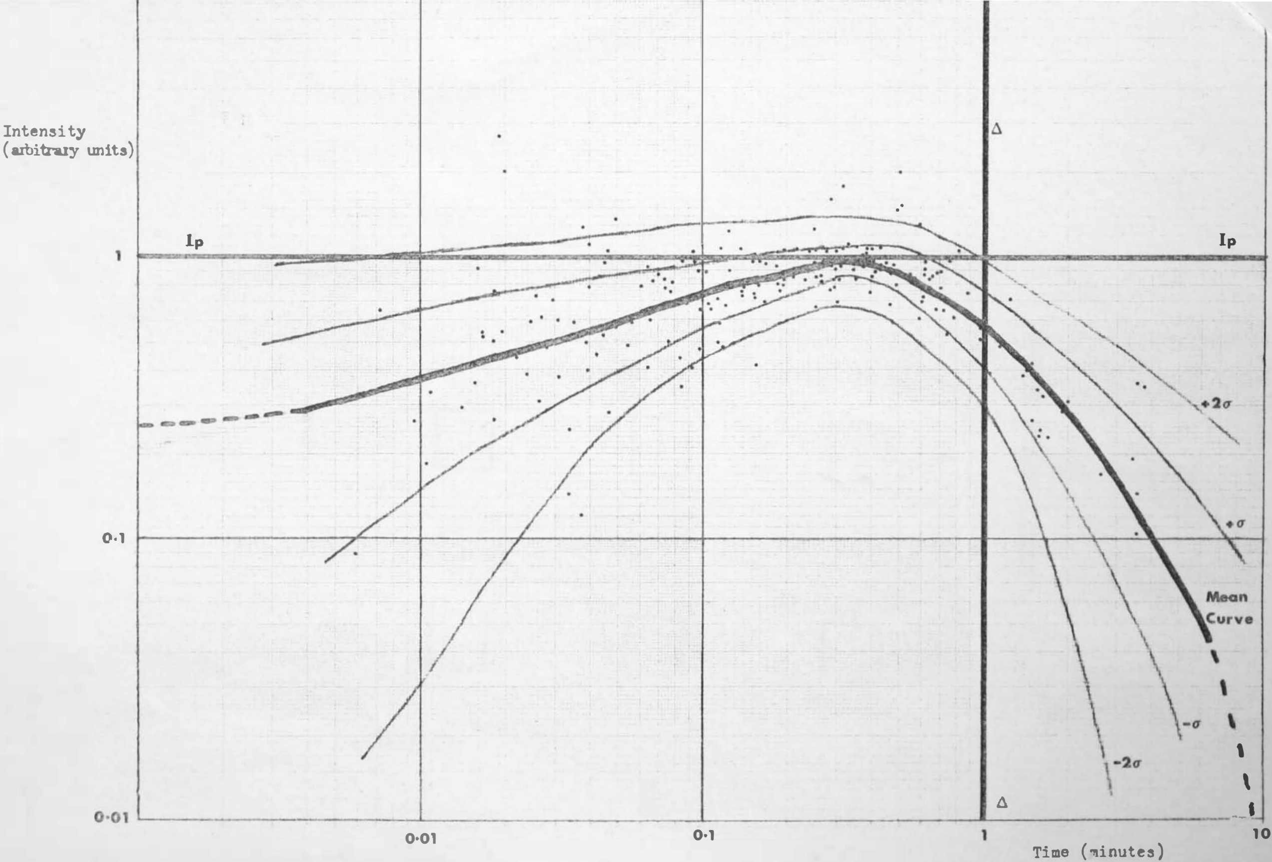


Fig.3 THE STANDARD INTENSITY-TIME CURVE, SHOWING THE SCATTER OF POINTS ABOUT IT.

Fig. 4 Burn 760-1

DURATIONS AT VARIOUS PLACES

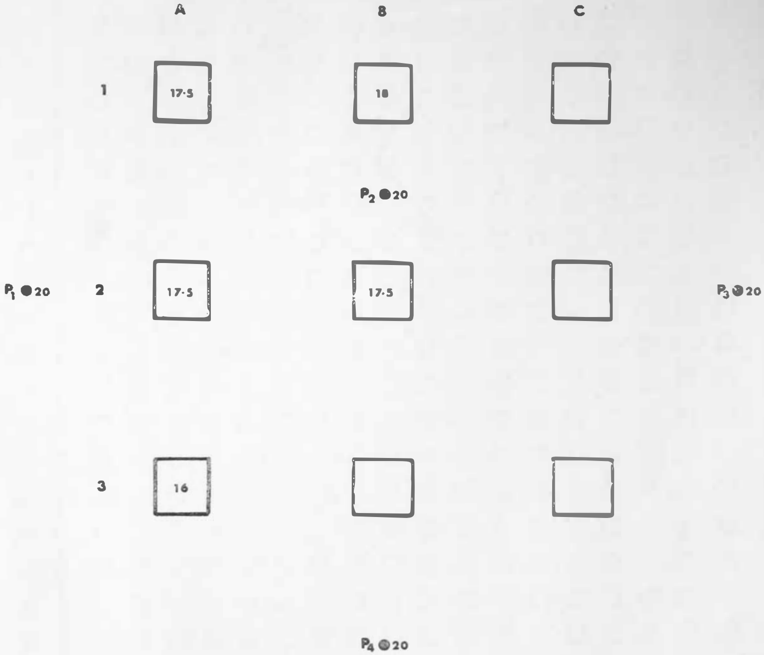
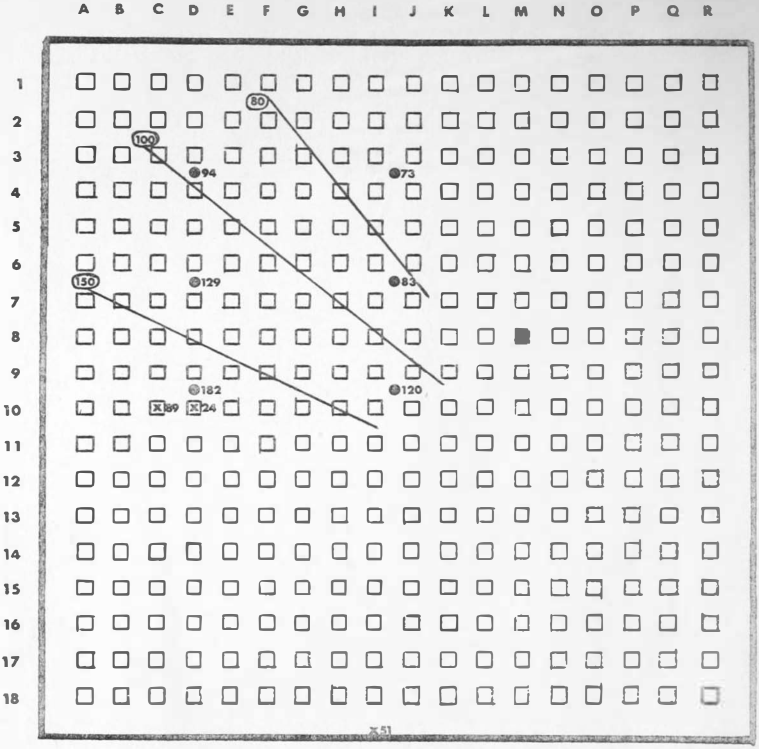


Fig. 5 Burn 460-14

DURATIONS AT VARIOUS PLACES



Note: Dots (●) are street temperature measurements, crosses (x) are others.

Contours based only on street temperatures.